

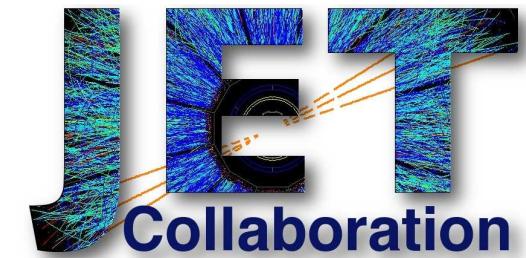
# VISHNU – a dynamical evolution model for heavy-ion collisions\*



DEPARTMENT OF  
**PHYSICS**

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Work done in collaboration with

**S.A. Bass, T. Hirano, P. Huovinen, Zhi Qiu, Chun Shen, and H. Song**

\*Supported by the U.S. Department of Energy (DOE)



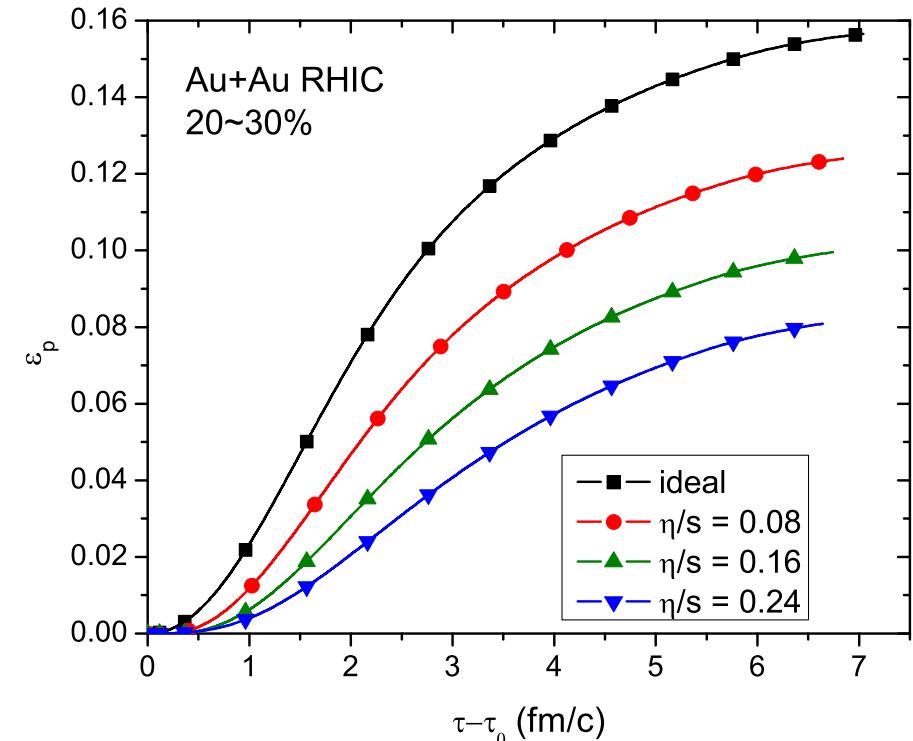
# Prologue: How to measure $(\eta/s)_{\text{QGP}}$

Hydrodynamics converts  
**spatial deformation of initial state**  $\Rightarrow$   
**momentum anisotropy of final state**,  
through anisotropic pressure gradients

**Shear viscosity** degrades conversion efficiency

$$\varepsilon_x = \frac{\langle\langle y^2 - x^2 \rangle\rangle}{\langle\langle y^2 + x^2 \rangle\rangle} \implies \varepsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$

of the fluid; the suppression of  $\varepsilon_p$  is monotonically related to  $\eta/s$ .



The observable that is most directly related to the total hydrodynamic momentum anisotropy  $\varepsilon_p$  is the **total ( $p_T$ -integrated) charged hadron elliptic flow  $v_2^{\text{ch}}$** :

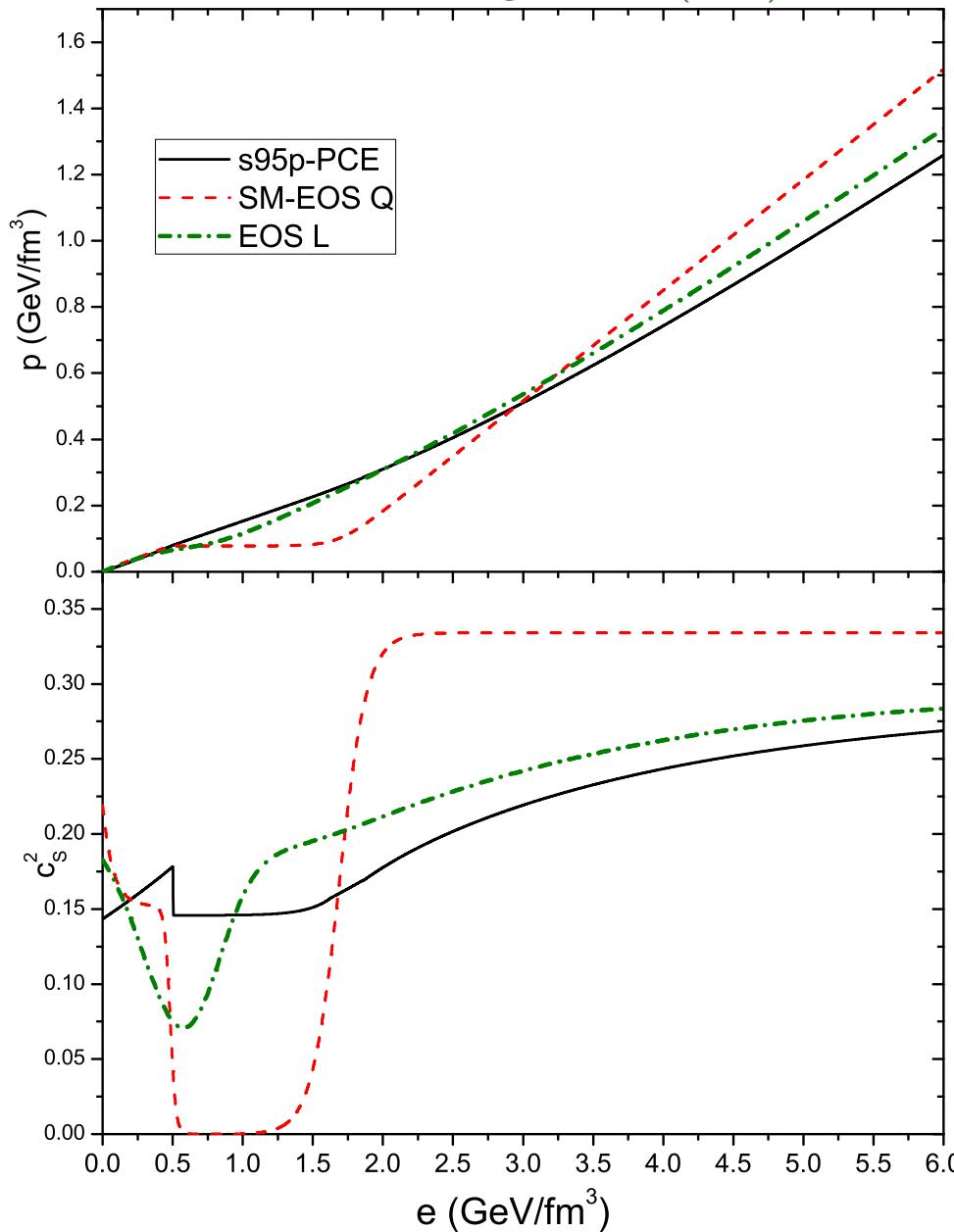
$$\varepsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle} \iff \frac{\sum_i \int p_T dp_T \int d\phi_p p_T^2 \cos(2\phi_p) \frac{dN_i}{dy p_T dp_T d\phi_p}}{\sum_i \int p_T dp_T \int d\phi_p p_T^2 \frac{dN_i}{dy p_T dp_T d\phi_p}} \iff v_2^{\text{ch}}$$

# Prologue: How to measure $(\eta/s)_{\text{QGP}}$ (ctd.)

- If  $\varepsilon_p$  **saturates** before hadronization (e.g. in PbPb@LHC (?))
  - ⇒  $v_2^{\text{ch}} \approx$  not affected by details of hadronic rescattering below  $T_c$   
**but:**  $v_2^{(i)}(p_T)$ ,  $\frac{dN_i}{dyd^2p_T}$  change during hadronic phase (addl. radial flow!), and these changes depend on details of the hadronic dynamics (chemical composition etc.)
  - ⇒  $v_2(p_T)$  of a single particle species **not** a good starting point for extracting  $\eta/s$
- If  $\varepsilon_p$  **does not saturate** before hadronization (e.g. AuAu@RHIC), dissipative hadronic dynamics affects not only the distribution of  $\varepsilon_p$  over hadronic species and in  $p_T$ , but even the final value of  $\varepsilon_p$  itself (from which we want to get  $\eta/s$ )
  - ⇒ need hybrid code that couples viscous hydrodynamic evolution of QGP to **realistic microscopic dynamics** of late-stage hadron gas phase
  - ⇒ **VISHNU** (“Viscous Israel-Steward Hydrodynamics ‘n’ UrQMD”)  
(Song, Bass, Heinz, PRC83 (2011) 024912) Note: this paper shows that UrQMD  $\neq$  viscous hydro!

# s95p-PCE: A realistic, lattice-QCD-based EOS

Huovinen, Petreczky, NPA 837 (2010) 26  
Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904

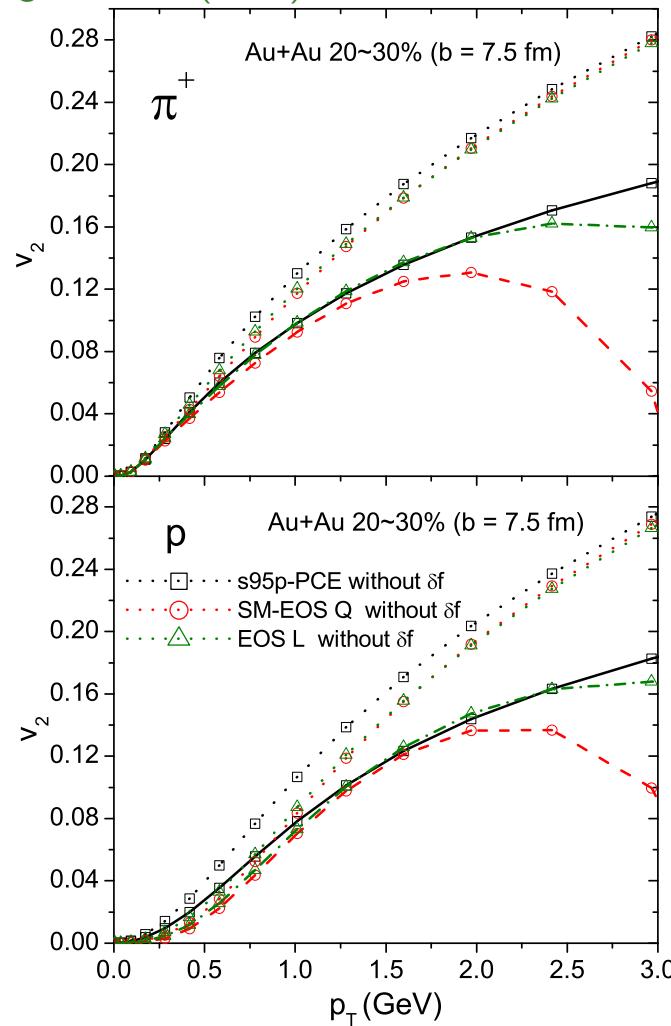
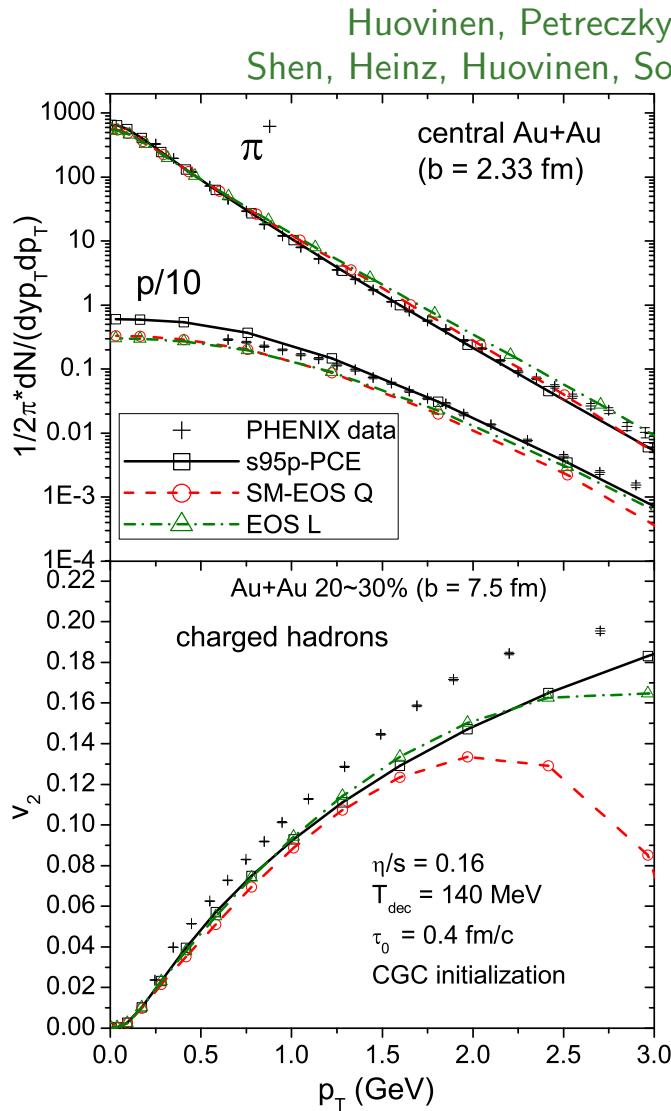


High  $T$ : Lattice QCD (latest hotQCD results)

Low  $T$ : Chemically frozen HRG ( $T_{\text{chem}} = 165 \text{ MeV}$ )

**No softest point!**

# s95p-PCE: A realistic, lattice-QCD-based EOS



Generates less radial flow than SM-EOS Q and EOS L but larger momentum anisotropy

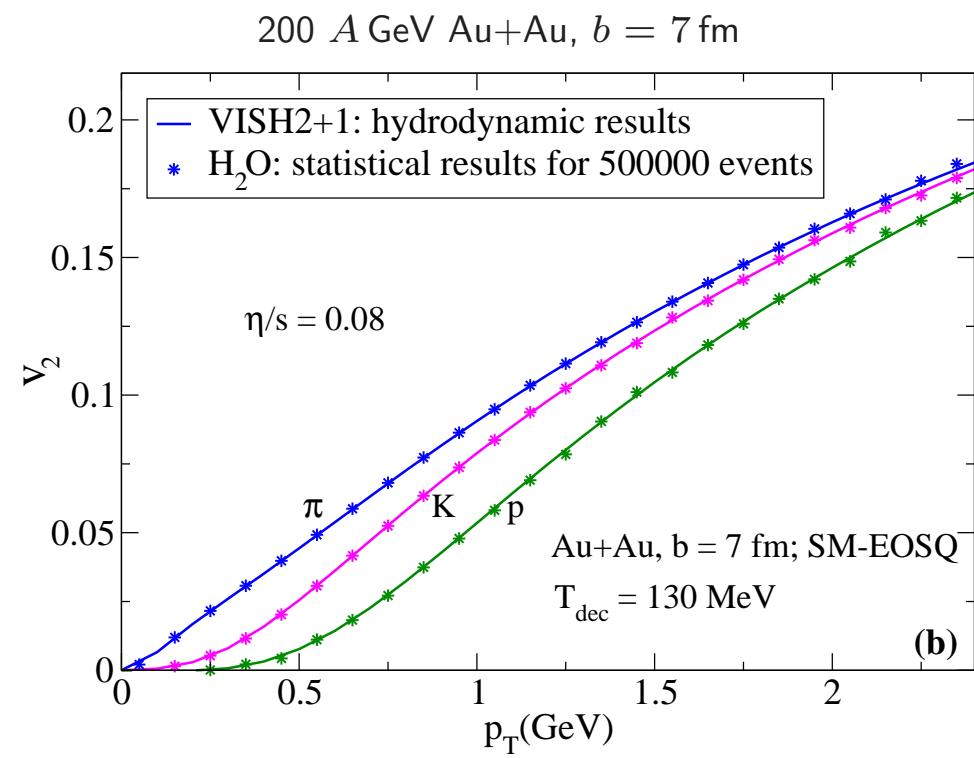
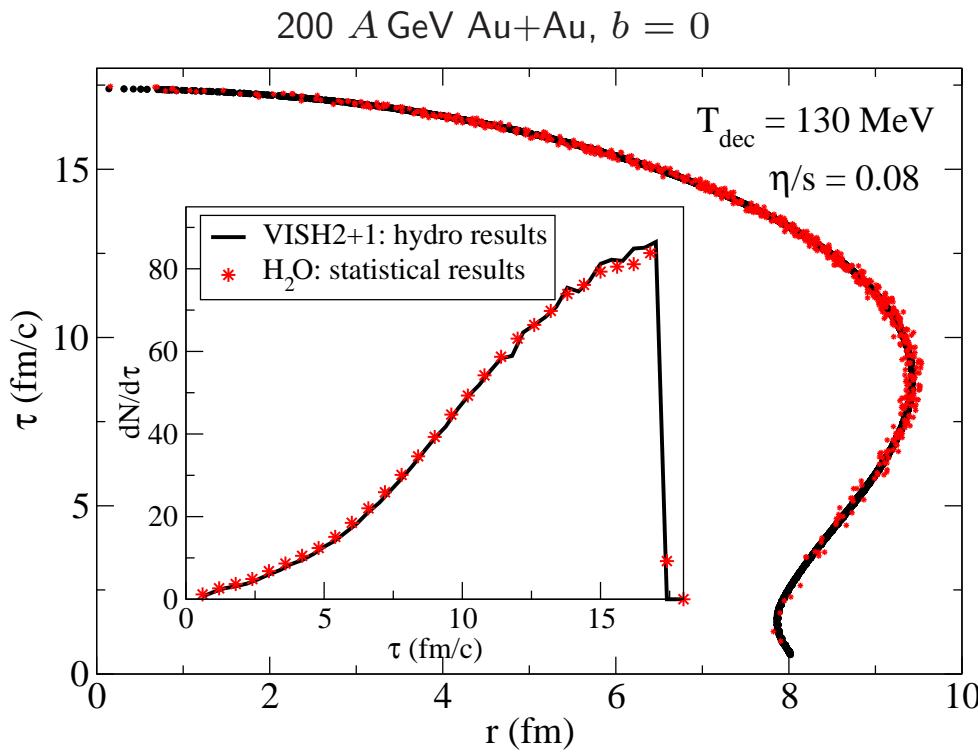
Smooth transition leads to smaller  $\delta f$  at freeze-out

$\implies$  larger  $v_2$

# $\text{H}_2\text{O}$ : Hydro-to-OSCAR converter

Monte-Carlo interface that samples hydrodynamic Cooper-Frye spectra (including viscous correction  $\delta f$ ) on conversion surface to generate particles at positions  $x_i^\mu$  with momenta  $p_i^\mu$  for subsequent propagation in UrQMD (or any other OSCAR-compatible hadron cascade afterburner)

Song, Bass, Heinz, PRC 83 (2011) 024912



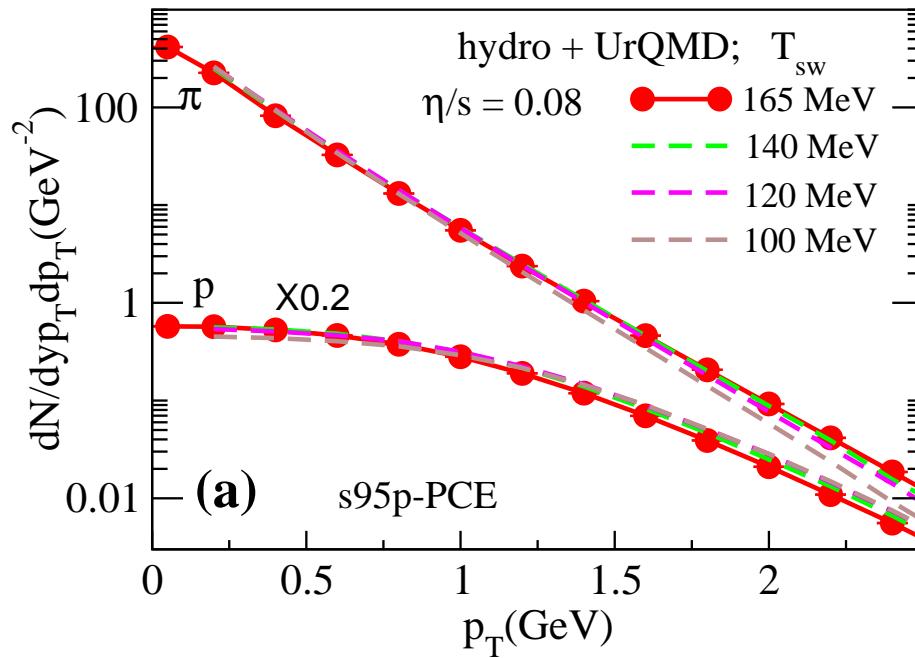
# VISHNU: hydro (VIOSH2+1) + cascade (UrQMD) hybrid

## Sensitivity to H<sub>2</sub>O switching temperature:

With chemically frozen EOS (s95p-PCE),  
 $p_T$ -spectra show very little sensitivity to  $T_{sw}$  (Teaney, 2000):

Song, Bass, Heinz, PRC 83 (2011) 024912

200  $A$  GeV Au+Au,  $b = 7$  fm



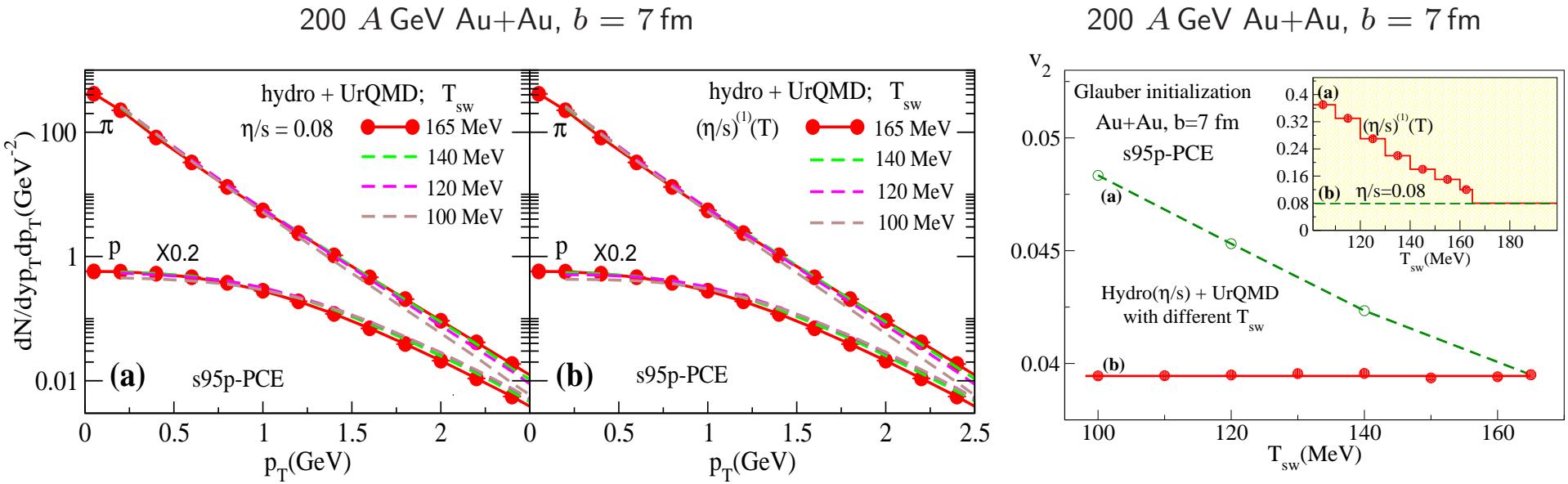
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## Sensitivity to H<sub>2</sub>O switching temperature:

With chemically frozen EOS (s95p-PCE),  
 $p_T$ -spectra show very little sensitivity to  $T_{sw}$

**but  $v_2$  does:**

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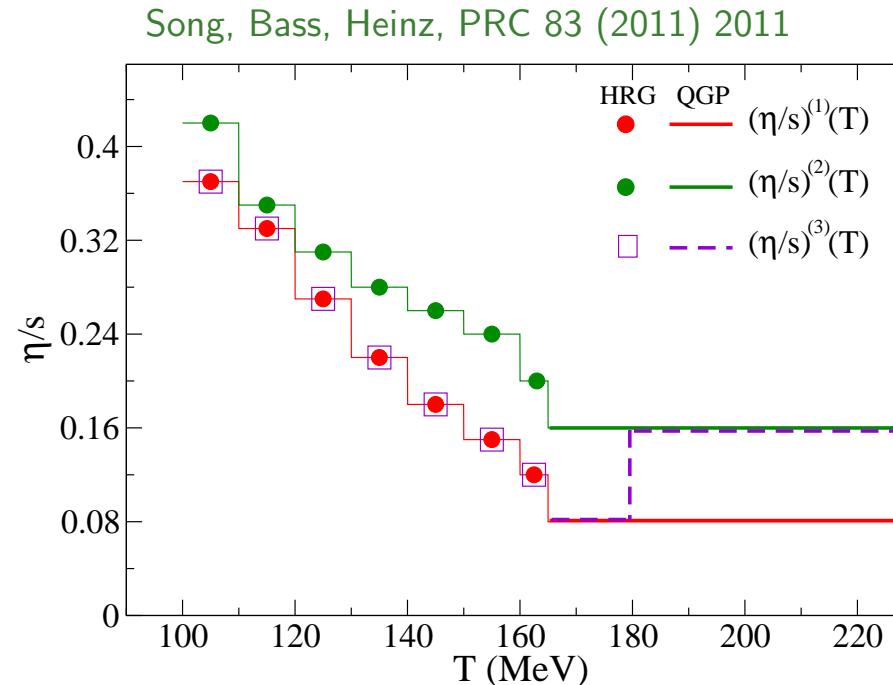


Viscous hydro with fixed  $\eta/s = 0.08$  generates more  $v_2$  below  $T_c$  than does UrQMD  
 $\implies$  UrQMD is more dissipative

VISH2+1 simulation of UrQMD dynamics requires  $T$ -dependent  $(\eta/s)(T)$  that increases towards lower temperature

# Is there a switching window in which UrQMD can be simulated by viscous hydro?

Unfortunately NO!



$(\eta/s)(T)$  extracted by trying to reproduce  $v_2$  independent of switching temperature depends on  $\delta_f$  input into UrQMD from hadronizing QGP

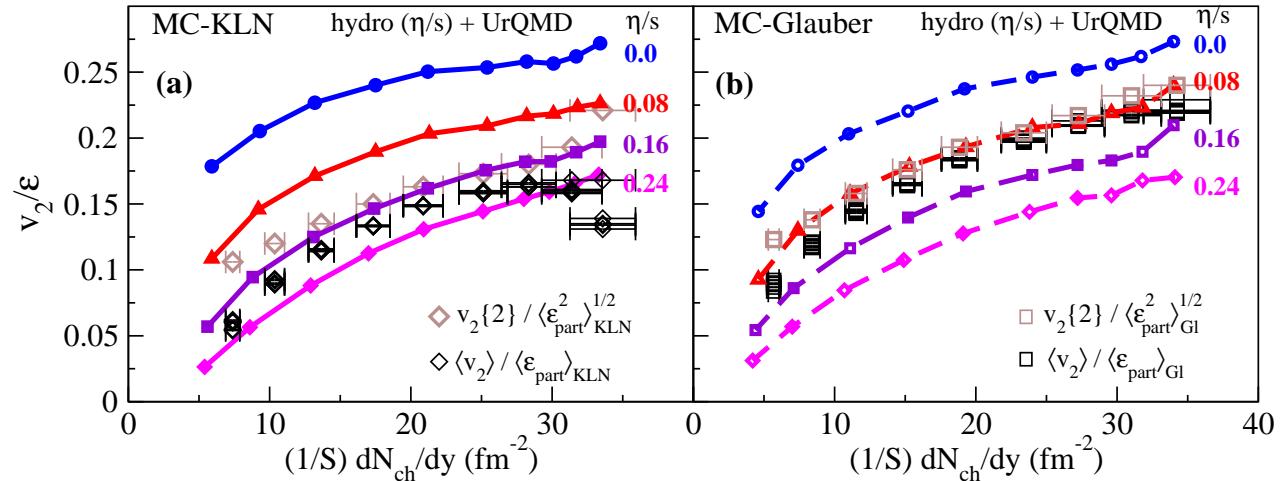
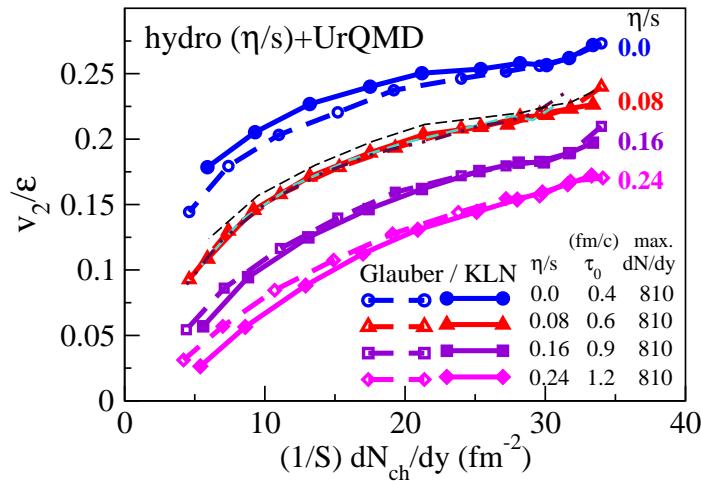
⇒  $\delta_f$  relaxes too slowly in UrQMD to be describable by viscous Israel-Stewart hydro

⇒ extracted  $(\eta/s)(T)$  not a proper UrQMD transport coefficient

⇒ **UrQMD dynamics can't be described by viscous Israel-Stewart hydrodynamics**

# Extraction of $(\eta/s)_{\text{QGP}}$ from AuAu@RHIC

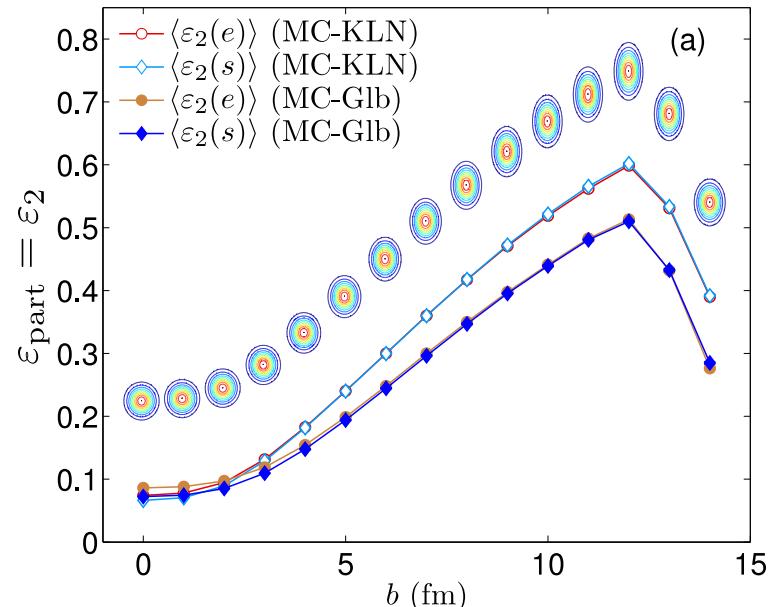
H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRL106 (2011) 192301



$$1 < 4\pi(\eta/s)_{\text{QGP}} < 2.5$$

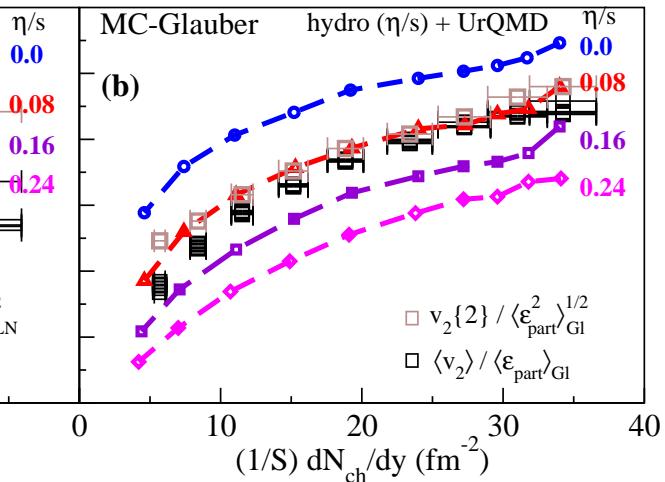
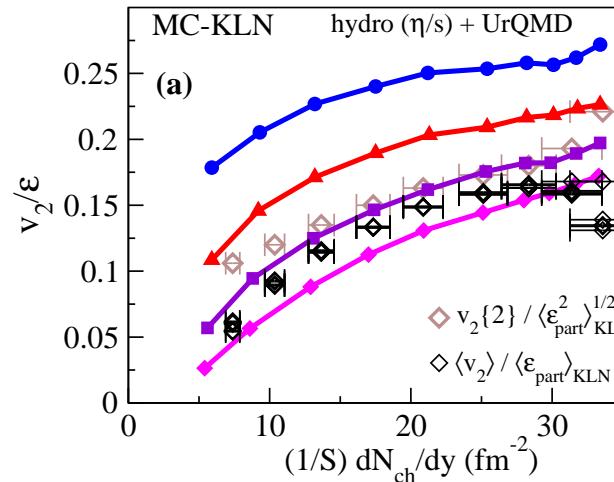
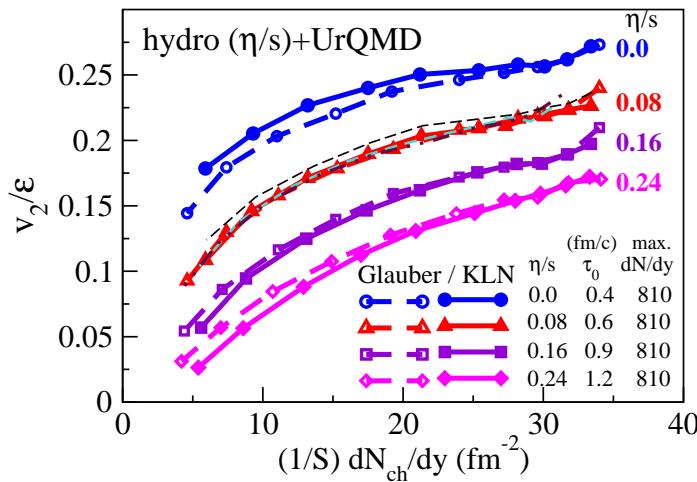
- All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as  $p_T$ -spectra of charged hadrons, pions and protons at all centralities
- $v_2^{\text{ch}}/\epsilon_x$  vs.  $(1/S)(dN_{\text{ch}}/dy)$  is “universal”, i.e. depends **only on**  $\eta/s$  but (in good approximation) not on initial-state model (Glauber vs. KLN, optical vs. MC, RP vs. PP average, etc.)
- dominant source of uncertainty:  $\epsilon_x^{\text{Gl}}$  vs.  $\epsilon_x^{\text{KLN}}$
- smaller effects: *early flow* → increases  $\frac{v_2}{\epsilon}$  by ∼ few % → larger  $\eta/s$
- bulk viscosity* → affects  $v_2^{\text{ch}}(p_T)$ , but ≈ not  $v_2^{\text{ch}}$

Zhi Qiu, U. Heinz, arXiv:1104.0650



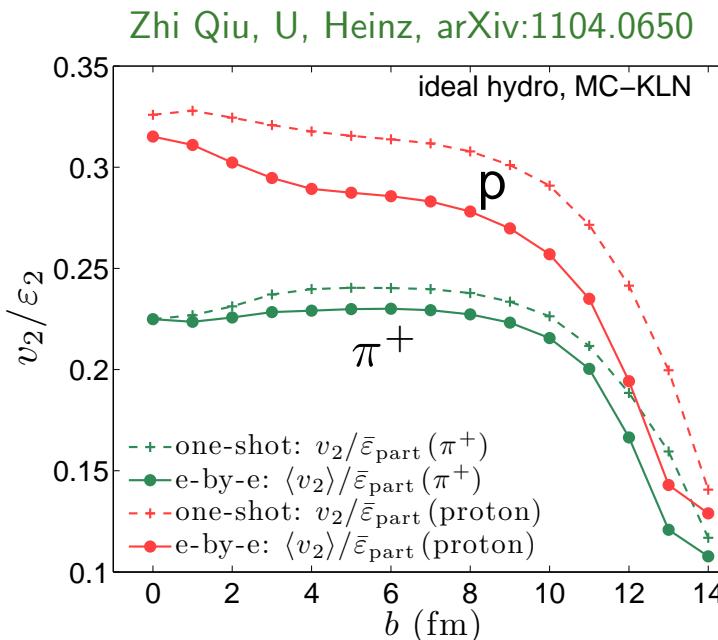
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H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRL106 (2011) 192301



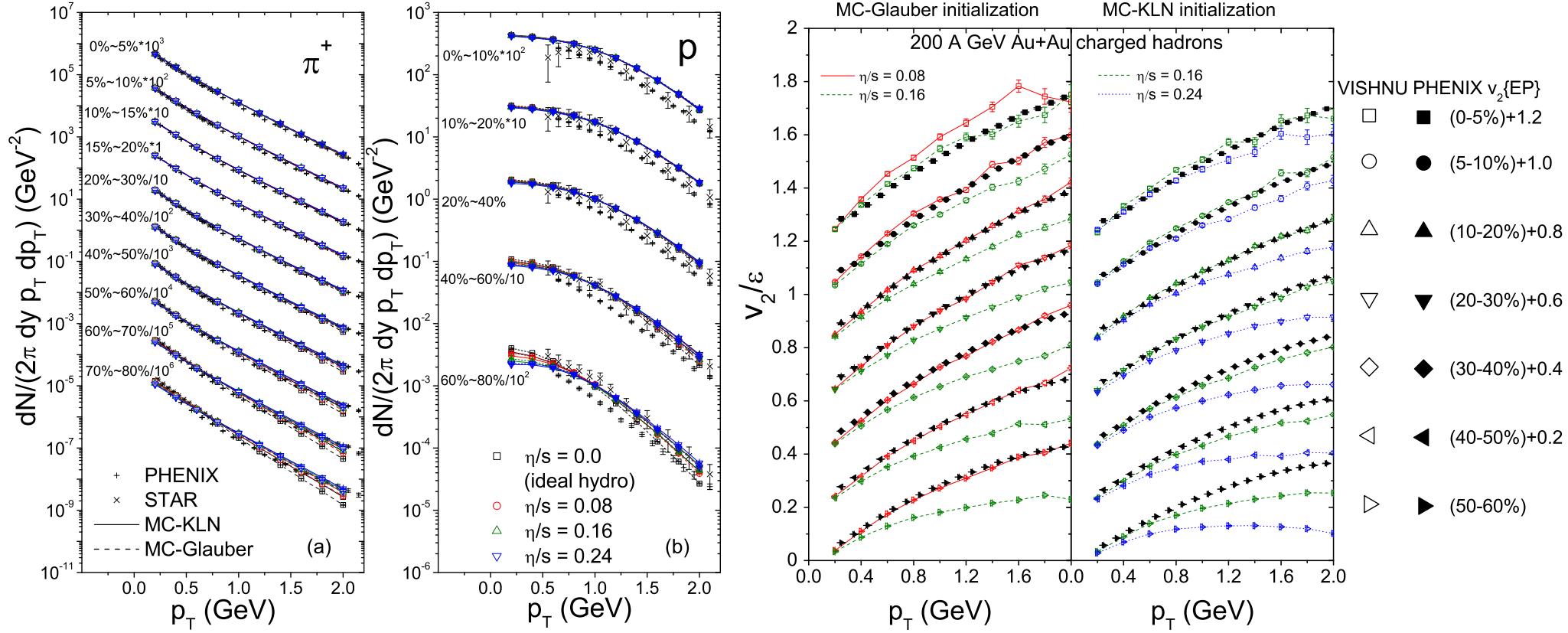
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*bulk viscosity* → affects  $v_2^{\text{ch}}(p_T)$ , but ≈ not  $v_2^{\text{ch}}$   
*e-by-e hydro* → decreases  $\frac{v_2}{\varepsilon}$  by  $\lesssim 5\%$  → smaller  $\eta/s$



# Global description of AuAu@RHIC spectra and $v_2$

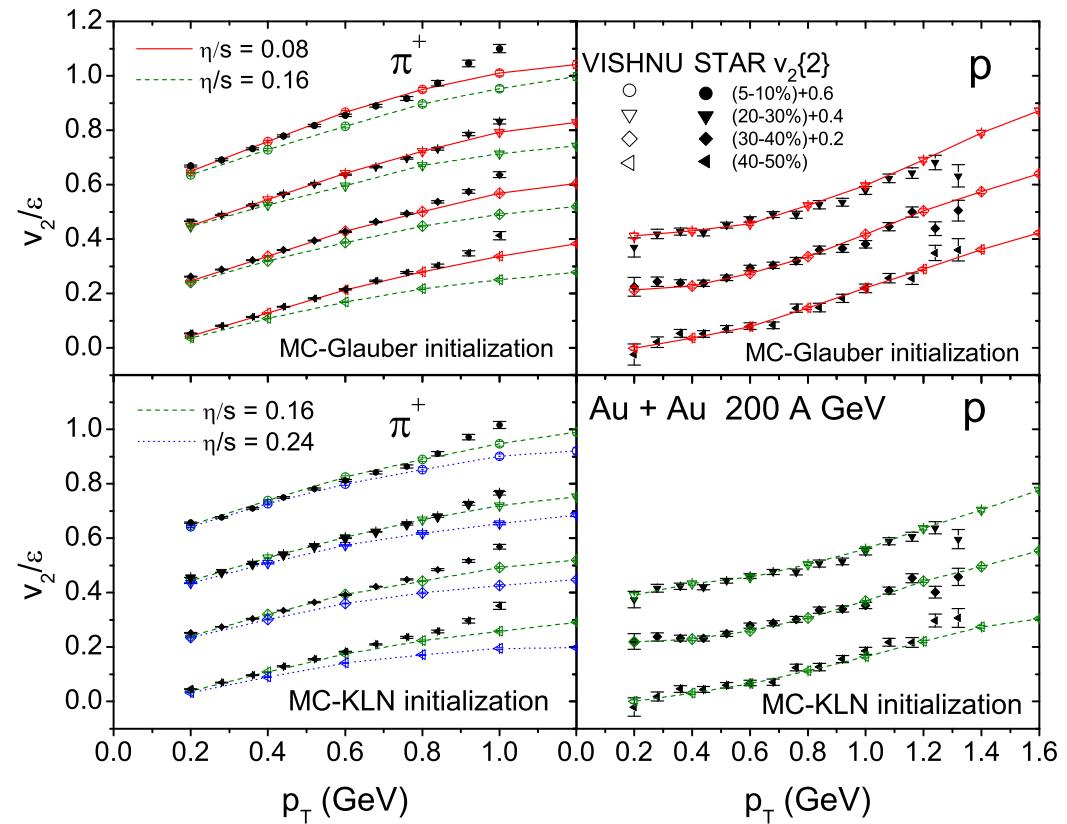
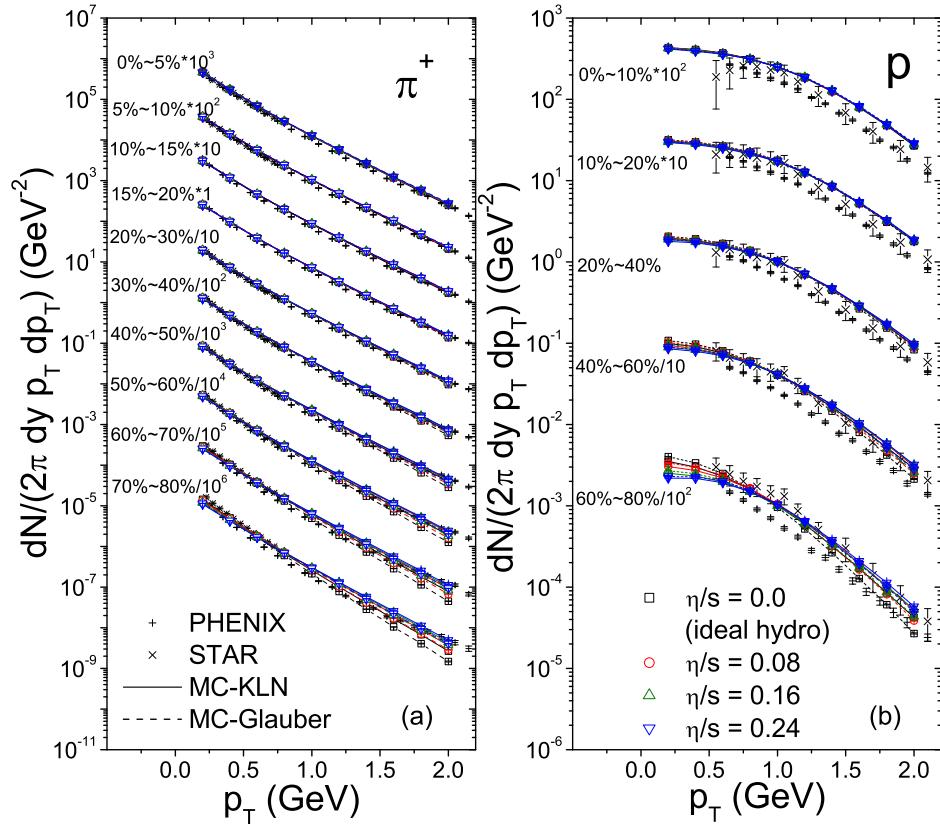
VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC 83 (2011) 054910)



- $(\eta/s)_{QGP} = 0.08$  for MC-Glauber and  $(\eta/s)_{QGP} = 0.16$  for MC-KLN work well for charged hadron, pion and proton spectra and  $v_2(p_T)$  at all collision centralities

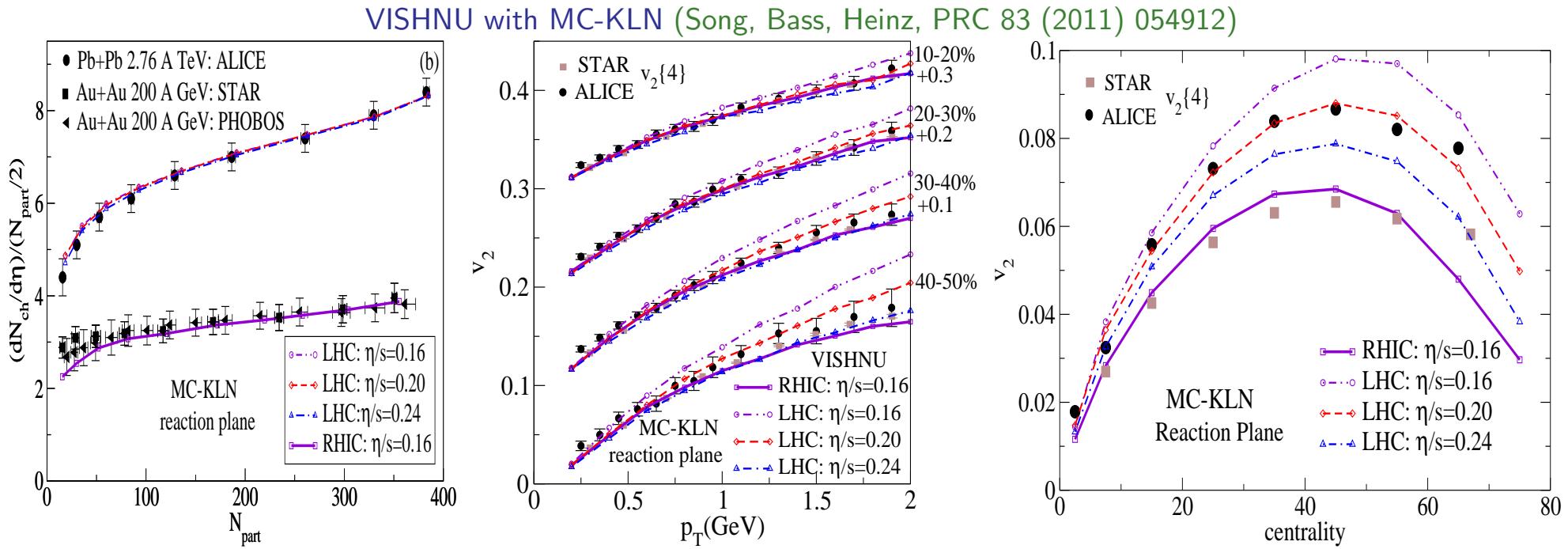
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- A **purely hydrodynamic model** (without UrQMD afterburner) with the same values of  $\eta/s$  does almost as well (except for centrality dependence of proton  $v_2(p_T)$ )
- Main difference: VISHNU develops more radial flow in the hadronic phase (larger shear viscosity), pure viscous hydro must start earlier than VISHNU ( $\tau_0 = 0.6$  instead of  $0.9 \text{ fm}/c$ ), otherwise proton spectra are too steep
- These  $\eta/s$  values agree with [Luzum & Romatschke, PRC78 \(2008\)](#), even though they used EOS with incorrect hadronic chemical composition  $\implies$  shows robustness of extracting  $\eta/s$  from total charged hadron  $v_2$

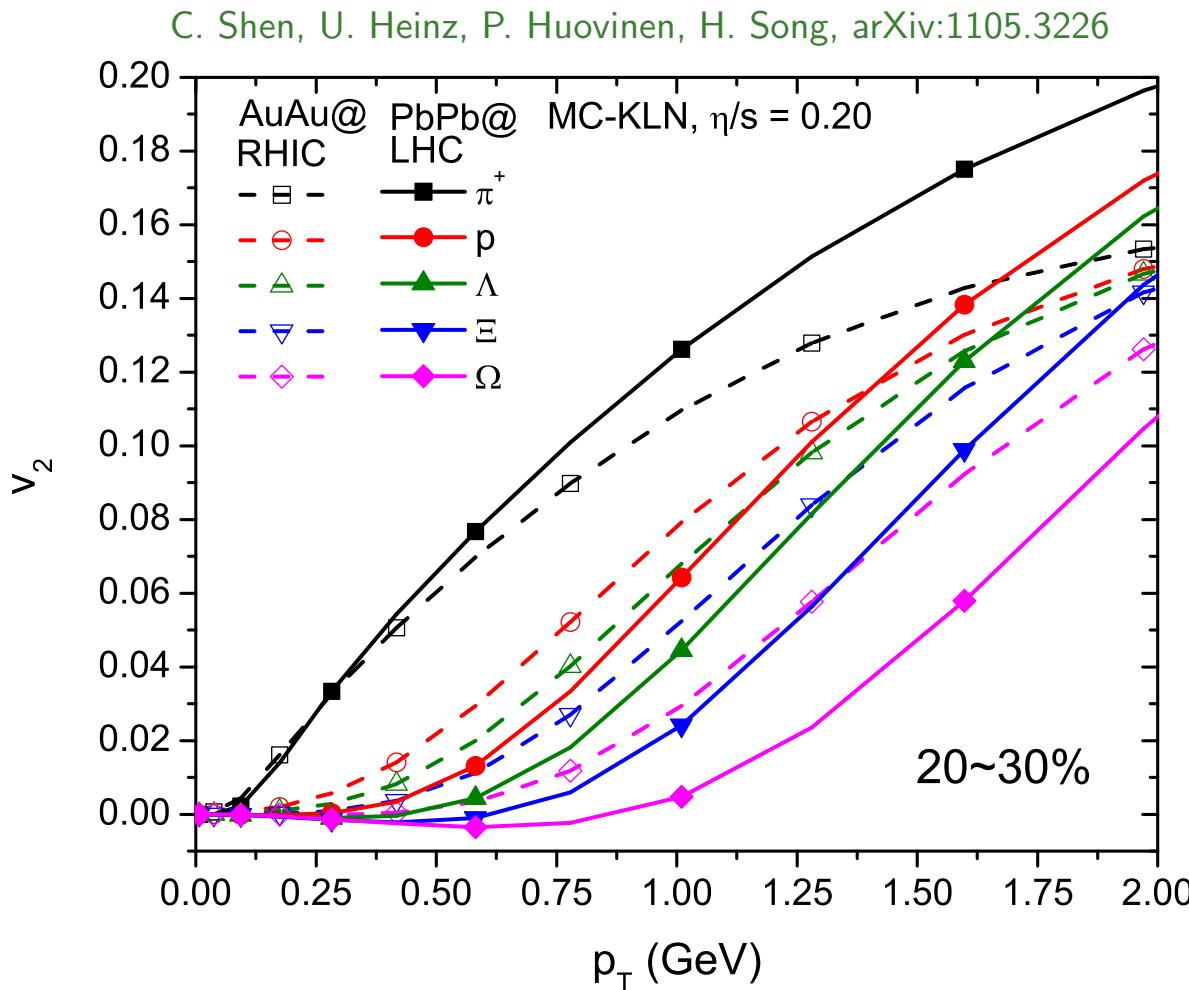
# Pre- and postdictions for PbPb@LHC



- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of  $dN_{ch}/d\eta$  well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{QGP} = 0.16$  for MC-KLN works well for charged hadron  $v_2(p_T)$  and integrated  $v_2$  in AuAu@RHIC, but overpredicts both by about 10-15% in PbPb@LHC
- Similar results from predictions based on pure viscous hydro  $\Rightarrow$  Shen et al., arXiv:1105.3226
- but:** At LHC, we see significant sensitivity of  $v_2$  to initialization of viscous pressure tensor  $\pi^{\mu\nu}$  (Navier-Stokes or zero), and it is not excluded that it may be possible to bring down  $v_2$  at LHC to the ALICE data without increasing  $\eta/s$  at higher  $T$  (requires more study)
- $\Rightarrow$  QGP at LHC perhaps a bit, but not dramatically more viscous than at RHIC!

# Why is $v_2^{\text{ch}}(p_T)$ the same at RHIC and LHC?

Answer: Pure accident! (Kestin & Heinz EPJC61 (2009) 545)



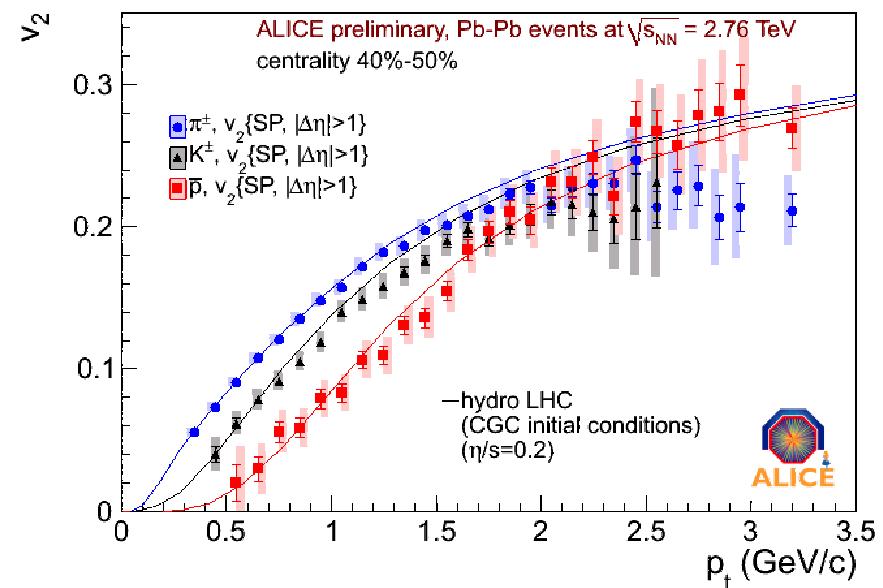
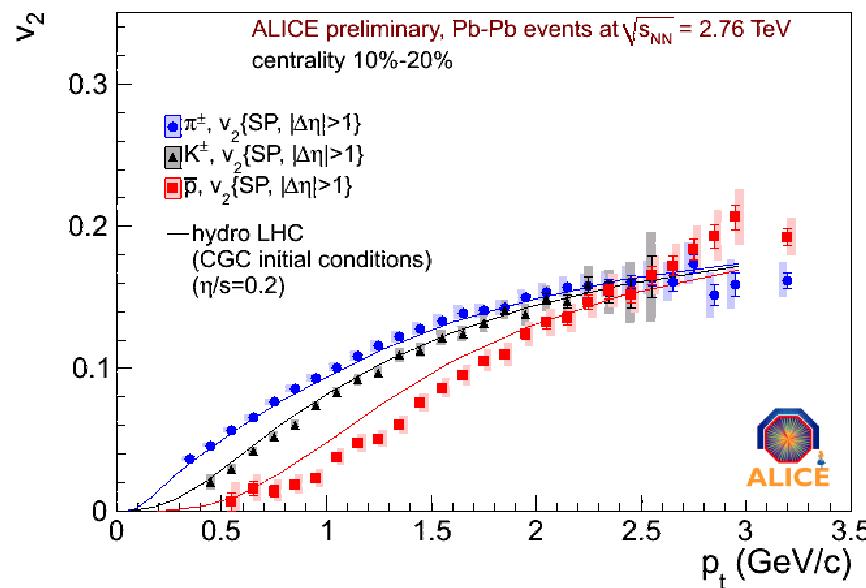
$v_2^\pi(p_T)$  increases a bit from RHIC to LHC, for heavier hadrons  $v_2(p_T)$  at fixed  $p_T$  decreases  
(radial flow pushes momentum anisotropy of heavy hadrons to larger  $p_T$ )

This is a hard prediction of hydrodynamics! (See also Nagle, Bearden, Zajc, arXiv:1102.0680)

# Successful prediction of $v_2(p_T)$ for identified hadrons in PbPb@LHC

Data: ALICE

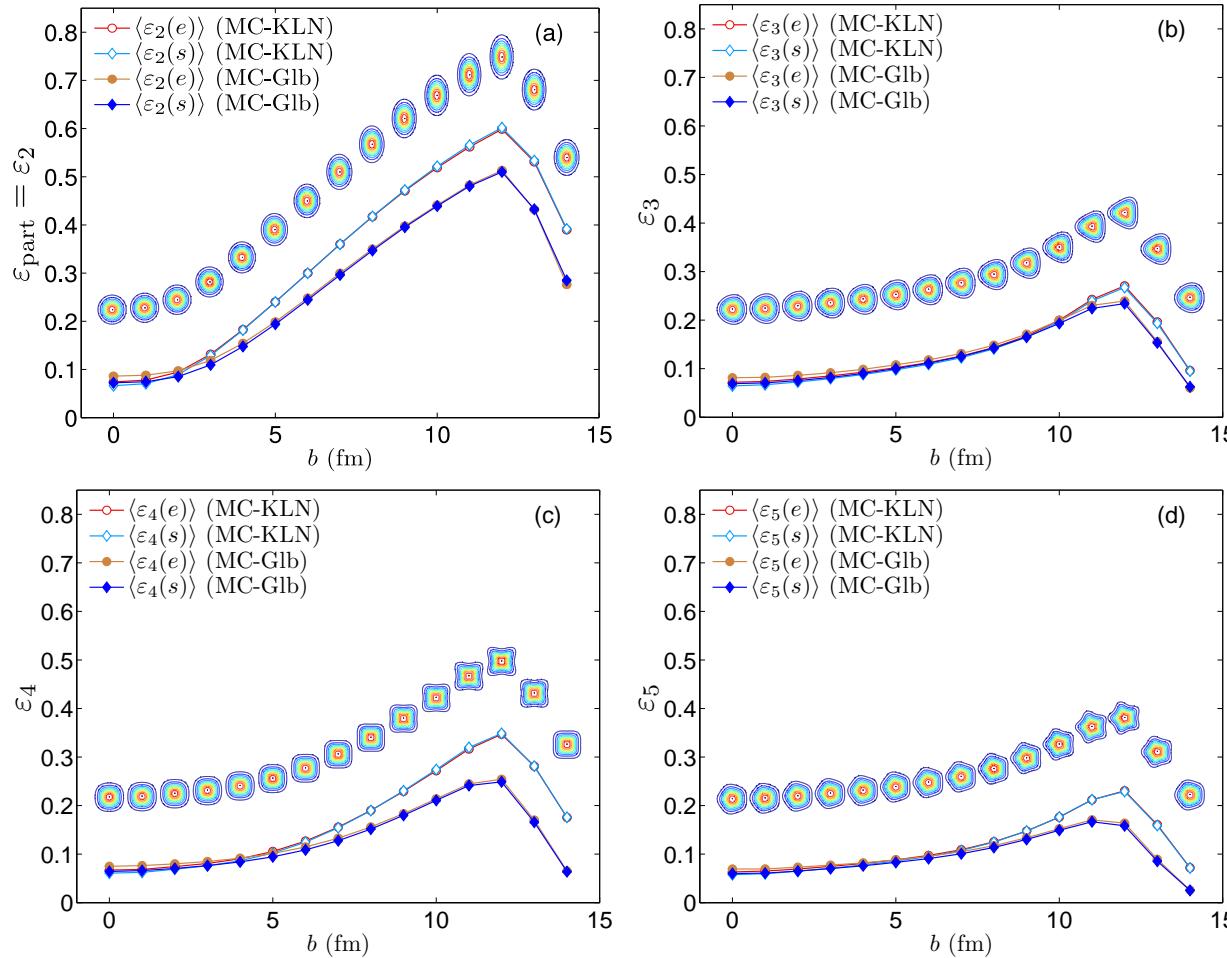
Lines: Shen et al., arXiv:1105.3226 (VISH2+1)



Perfect fit in semi-peripheral collisions, but not enough proton radial flow in central collisions  $\Rightarrow$  hadronic cascade (VISHNU) may help

# Back to the elephant in the room: How to eliminate the large model uncertainty in the initial eccentricity?

Zhi Qiu and U. Heinz, arXiv:1104.0650



Initial eccentricities  $\varepsilon_n$  and angles  $\psi_n$ :

$$\varepsilon_n e^{in\psi_n} = - \frac{\int r dr d\phi r^2 e^{in\phi} e(r, \phi)}{\int r dr d\phi r^2 e(r, \phi)}$$

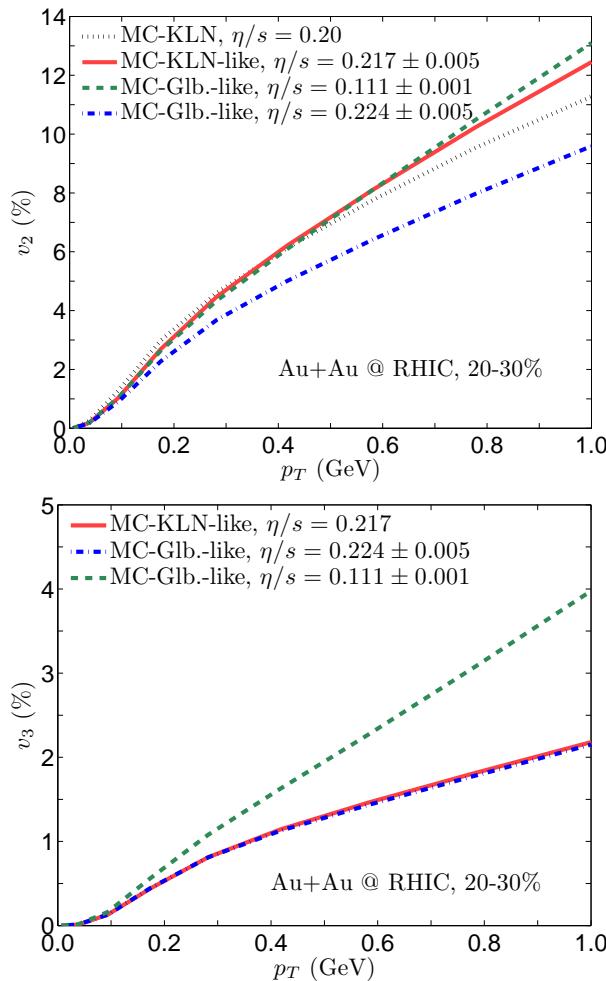
- MC-KLN has larger  $\varepsilon_2$  and  $\varepsilon_4$ , but similar  $\varepsilon_5$  and almost identical  $\varepsilon_3$  as MC-Glauber
- Angles of  $\varepsilon_2$  and  $\varepsilon_4$  are correlated with reaction plane by geometry, whereas those of  $\varepsilon_3$  and  $\varepsilon_5$  are random (purely fluctuation-driven)
- While  $v_4$  and  $v_5$  have mode-coupling contributions from  $\varepsilon_2$ ,  $v_3$  is almost pure response to  $\varepsilon_3$  and  $v_3/\varepsilon_3 \approx \text{const.}$  over a wide range of centralities (for details see arXiv:1104.0650)

⇒ Idea: Use total charged hadron  $v_3^{\text{ch}}$  to determine  $(\eta/s)_{\text{QGP}}$ ,  
then check  $v_2^{\text{ch}}$  to distinguish between MC-KLN and MC-Glauber!

# Shooting the elephant

## Proof of principle calculation:

Zhi Qiu and U. Heinz, to be published



- Take ensemble of sum of deformed Gaussian profiles,  $s(\mathbf{r}_\perp) = s_2(\mathbf{r}_\perp; \tilde{\varepsilon}_2, \psi_2) + s_3(\mathbf{r}_\perp; \tilde{\varepsilon}_3, \psi_3)$ , with
  1. equal Gaussian radii  $R_2^2 = R_3^2 = 8 \text{ fm}^2$  to reproduce  $\langle r_\perp^2 \rangle$  of MC-KLN source for 20-30% AuAu
  2.  $\tilde{\varepsilon}_2$  and  $\tilde{\varepsilon}_3$  adjusted such that
    - $\bar{\varepsilon}_{2,3} = \langle \varepsilon_{2,3} \rangle_{\text{KLN}}^{20-30\%}$  ("MC-KLN-like")
    - $\bar{\varepsilon}_{2,3} = \langle \varepsilon_{2,3} \rangle_{\text{GI}}^{20-30\%}$  ("MC-Glauber-like")
  3.  $\psi_2 = 0, \psi_3$  (direction of triangularity) distributed randomly
- Use  $v_2^\pi(p_T)$  from VISH2+1 for  $\eta/s = 0.20$  with MC-KLN initial conditions for 20-30% AuAu as "mock data"
- Fit mock  $v_2^\pi(p_T)$  data with VISH2+1 for "MC-Glauber-like" or "MC-KLN-like" Gaussian initial conditions with both elliptic and triangular deformations by adjusting  $\eta/s$ 
 $\implies (\eta/s)_{\text{KLN}} = 0.217 \pm 0.005$  for "MC-KLN-like",  
 $(\eta/s)_{\text{GI}} = 0.111 \pm 0.001$  for "MC-Glauber-like"
- Compute  $v_3^\pi(p_T)$  for "MC-KLN-like" fit with  $(\eta/s)_{\text{GI}}=0.217$  and reproduce it with "MC-Glauber-like" initial condition by readjusting  $\eta/s$ 
 $\implies (\eta/s)_{\text{GI}}^{v_3} = 0.224 \pm 0.005$  for "MC-Glauber-like"
- Compute  $v_2^\pi(p_T)$  for "MC-Glauber-like" initial profiles with readjusted  $(\eta/s)_{\text{GI}}^{v_3} = 0.224$  and compare with "MC-Glauber-like" fit to original mock data  $\implies$  clearly visible (and measurable) difference!

This exercise proves: (i) Fitting  $v_3(p_T)$  data with MC-Glauber and MC-KLN initial conditions yields **the same  $\eta/s$**  (within narrow error band); (ii) The corresponding  $v_2(p_T)$  fits are quite different, and **only one** (more precisely: at most one!) of the models **will fit the corresponding  $v_2(p_T)$  data.**

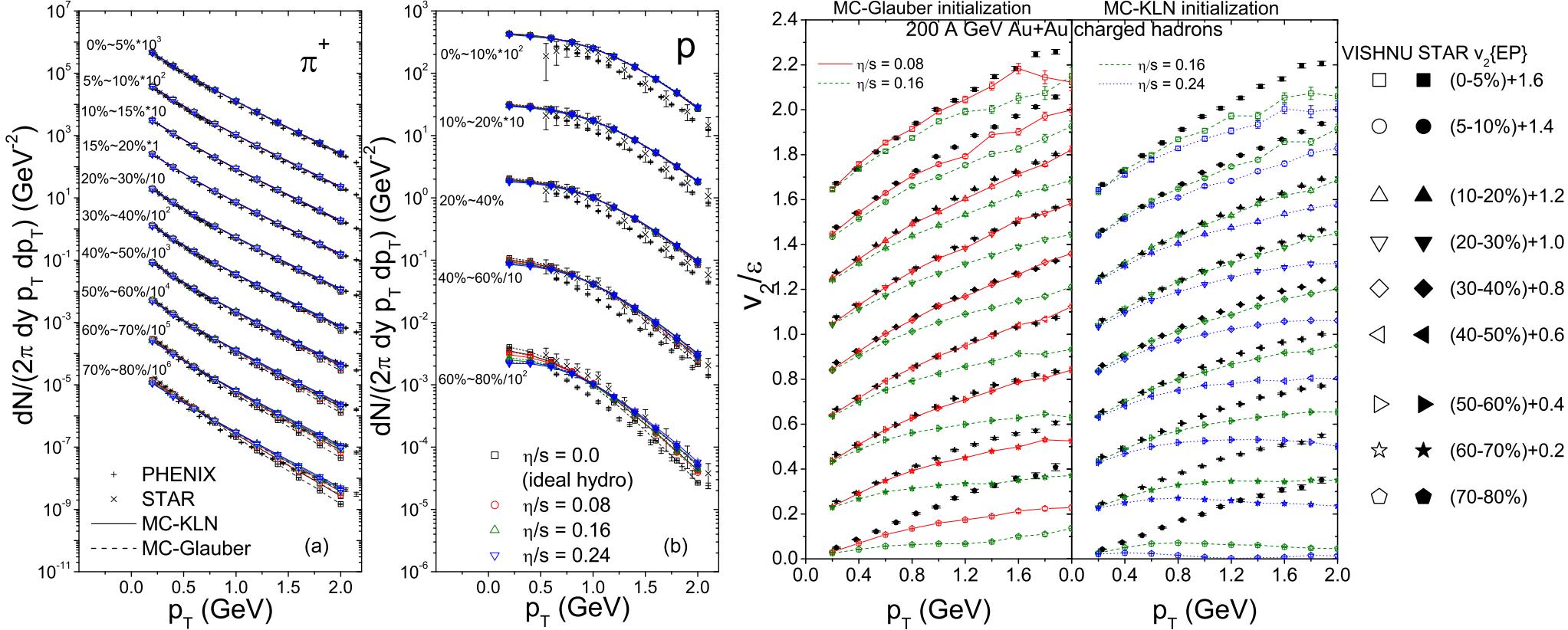
# Conclusions

- Hybrid codes (e.g. VISHNU) that couple viscous hydro evolution of QGP to microscopic hadron cascade now allow a determination of  $(\eta/s)_{QGP}$  with  $\mathcal{O}(25\%)$  precision **if the initial fireball eccentricity is known to better than 5% relative accuracy**
- With VISHNU good global fits that describe **all single-particle observables for soft hadron production** (spectra, elliptic flow) at all but the most peripheral AuAu collision centralities are obtained, for both MC-Glauber and MC-KLN initial conditions, by using  $(\eta/s)_{QGP} = 0.08$  for MC-Glauber and  $(\eta/s)_{QGP} = 0.16–0.20$  for MC-Glauber
- **Event-by-event hydrodynamics** with fluctuating initial conditions yields somewhat less  $v_2/\varepsilon_2$  than single-shot hydro with smooth average initial profiles  $\Rightarrow$  this will bring  $(\eta/s)_{QGP}$  from charged hadrons down by  $\sim 0.02 – 0.03$ . For proton  $v_2$ , event-by-event hydro matters a lot.
- While MC-Glauber and MC-KLN give  $\varepsilon_2$  that differ by 20-25%, they give almost identical  $\varepsilon_3$  (which is not geometric but fluctuation-driven). **Only one of them will be able to fit simultaneously both  $v_2$  and  $v_3$ .**
- This may enable us to gain the necessary control over initial conditions to make a precise (i.e. better than factor 2) measurement of  $(\eta/s)_{QGP}$ .

# Supplements

# Global description of AuAu@RHIC spectra and $v_2$

VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC 83 (2011) 054910)



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